EVS24
Stavanger, Norway, May 13-16, 2009

High Efficiency Bicycle Propulsion System Using Two Motors and Epicyclic Gearing

Per H. Sørensen[1], Miles Hellon[2]
[1]*Forsandveien 13, 4307 Sandnes, Norway, perhassel@gmail.com*
[2]*38 Winforton Street, London SE10 8UR, U.K., mileshellon@hotmail.com*

Abstract

This paper describes a novel propulsion unit for cycles and other ultralight vehicles using two brushless DC (BLDC) motors feeding sun and ring gear of an epicyclic gear unit all within a single enclosure. The two BLDC motors having different operating characteristics are being actively managed using a microprocessor connected to two electronic commutation controllers, one for each motor. By optimizing the RPM for each motor according to vehicle speed and torque the main propulsion motor and its controller is kept working within its maximum efficiency band. Most of the electric energy is used by this motor and controller pair maintaining total efficiency at a high level.

Keywords: bicycle, brushless motor, efficiency, planetary gear, powertrain

1 Introduction

The single biggest obstacle for electric vehicles is the high cost of energy storage, both in terms of investment and in added weight to the vehicle [1].

For shorter distances electric bicycles are a smart choice as their energy requirement is much less than a car-sized electric vehicle [2][3]. They are now used in large numbers but mostly on flat terrain [4].

As a commuter vehicle for hilly terrain electric bicycles need refinement. This paper discuss a propulsion unit for electric bicycles and other ultralight electric vehicles that increases the efficiency and versatility of the powertrain by adding a electromechanical variable gearing.

1.1 Current Electric Bicycle Motors

Currently, most commercial electric bicycle motors are hub motors with or without a fixed gearing. Alternatively, some motors are part of the pedal arrangement and their power is transferred to the wheel using the same bicycle chain as the cyclist. Sometimes friction drive, direct to the tyre or rim, is used. All the existing solutions involves some form of compromise as can be seen from table 1.

1.2 Lack of Gearing

Of the commercially used motor solutions, only those which drive via the bicycle's chain can be geared. The other solutions use a single gear or drive the wheel directly.
Gearing is important to match the RPM band where the motor is efficient with the speed of the bicycle which depends on the available motor power and the current road condition and bicycle load.
With limited power available due to legal reasons and battery range issues, the lack of gearing is an important limitation, especially in hilly terrain [5].

Table1: Motor comparison

Motor type:	Major issues:
Hub motor, direct	*Low power to weight ratio, low torque, motor drag when coasting, special wheel required*
Hub motor, geared	*no regeneration due to integral freewheel, special wheel required*
Friction motor	*Low torque, slippery when wet, wear on tyre,no regeneration due to integral freewheel*
Motor using existing chain	*no regeneration, special freewheel required for pedals, rapid chain wear, difficult with derailleur gear*
Motor with own chain/belt	*Extra pulley normally require hub for disc brakes, more awkward wheel removal*

2 New Design Based on Dual Motor Propulsion

Avoiding the limitations of commercially available e-bike propulsion systems required some form of speed adaptation. Using a form of differential, or epicyclic gearing, similar to that used by the Toyota Prius, it became clear that a suitable matching of motor speed to vehicle speed was possible without manual gearing, by adding a smaller extra motor [6][13].

Using motor and gear designs optimized for this application a compact unit has been designed and modelled in 3D for simulation and prototyping as illustrated in figure 1.

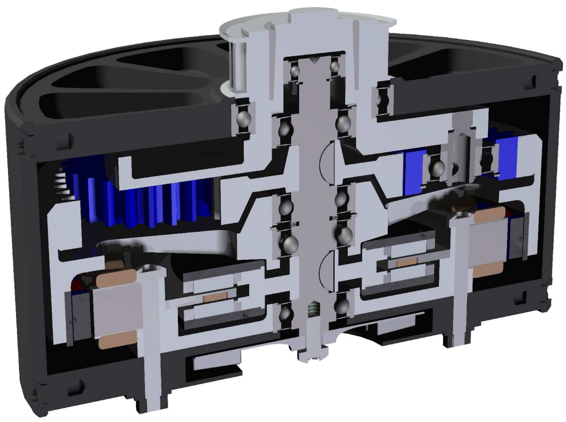

Figure 1: Cross Section of Complete Propulsion Unit

2.1 Epicyclic Gearing

The use of epicyclic gears, often called planetary gears, is common on bicycles where they have been used inside hub gears for years [7].

When used as a differential in a car, the two output shafts supply the motor power to each wheel. If one wheel is stationary, the other wheel spins twice as fast.

Here it is used the opposite way, having two motors driving two input shafts. This results in output speed being controlled by the sum of the two motor speeds.

When designing the gearing ratio of the epicyclic gearing the torque ratio between the motors can be adapted to suit the selected motors.

2.2 Final Gearing Ratio

Final gearing is by belt drive to the bicycle wheel, or alternatively, a second epicyclic gear for a hub motor version. Ratio is selected to match propulsion unit RPM range to bicycle speed range.

2.3 Motors and Electronic Control

The main propulsion motor is designed to supply high torque and run at a moderate speed. The gearing motor has much lower torque but can run at a much higher speed. The speed of each motor is controlled by a microcontroller. The microcontroller strives to maintain the propulsion motor at its most efficient RPM and uses the gearing motor to adapt the propulsion unit's output speed to the bicycle speed.

3 Detailed Description of Design

A prototype design has been made based on the principles of the suggested propulsion unit. This prototype design will be described in detail.

3.1 Motor Location

For the prototype design, a non-hub propulsion unit using a separate belt was selected. This makes the design adaptable to velomobiles or other ultralight vehicles where hub motors don't fit. It also reduces the unsprung weight on suspension bicycles, improving road grip. Finally, hub motors are mechanically more complex due to space limitations and dynamic load issues.

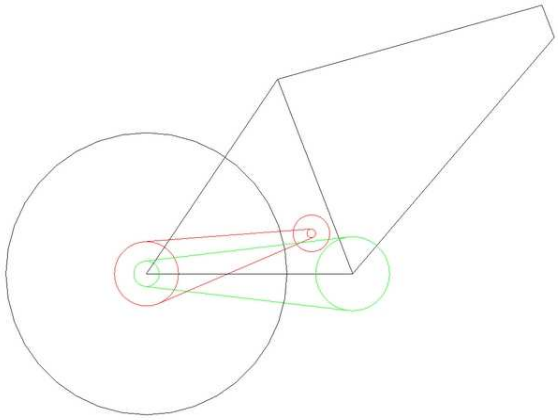

Figure 2: Motor Location

A hub motor version is possible, but would require a second stage epicyclic gear for final gearing. This would also require a stronger housing to support wheel and spoke loads, increasing the weight. If used on a rear wheel it would also need to support the chain gear.

3.2 Motor RPM Limitations

When linking the motor to the wheel without a freewheeling mechanism, regenerative braking becomes available, but at the same time it also allows over-revving of the motor.
Every motor has an absolute maximum RPM limit and will be destroyed if this speed is exceeded.
Direct driven hub motors usually have an RPM limit higher than wheel RPM possible on a bicycle, unfortunately this is not the case with geared motors. Therefore geared hub motors and motors using the bicycle chain have a built-in freewheel mechanism that prevents the motor from being turned by the wheel. But a freewheel also prevents the regenerative braking used to improve battery range and prolong lifetime of the cycle brakes.

In this new design the maximum allowable wheel speed is increased by dividing the wheel speed on two motors via the epicyclic gear. It becomes possible to extend available speed range beyond what a single motor can handle alone and still do regenerative braking.

3.3 Motor Fan

By adding a small fan to the high revving gearing motor axle it is possible to do forced cooling on the motor housing and attached components to reduce temperature and increase power output. By accurate controlling the speed of both motors and by making them counter rotate the fan can be used even when the bicycle is stationary. This fan can be used for the motor and/or cooling power electronics.

3.4 Sensorless Motors

Two different types of brushless DC motor commutation exists, with or without sensors.
Most bicycle motors uses hall sensors for commutation control but some do not and are referred to as having sensorless commutation [8].

Unfortunately sensor based commutation requires more parts inside the motor and more connections between motor and controller. That is the reason why sensorless design is preferred.

Sensorless commutation uses induced voltages to sense rotor position. In order to get induced voltages, the rotor must move. For pedal assisted electric bicycles it is possible to use sensorless commutation by having the user start moving the cycle before the motor is energized. For other applications the motor start-up will make disturbing erratic movements forcing motor manufacturers to use sensors.

With the dual motor principle, sensorless commutation can be used for both motors. By energizing both motors at the same time but counter rotating, they will not move the bicycle. This way sensorless commutation is possible and the problems normally associated with sensorless commutation are eliminated.

3.5 Coreless Motor

For coasting, a motor able to rotate at high RPM with negligible losses is required for the gearing motor.

To achieve this, a disc type motor with rotating axial field, having two parallel PM rotors with air core coils is selected.

3.6 Reduction of Loss

When a permanent magnet motor is forced to rotate it will induce voltage in the windings. Rotation will also cause eddy current losses in all conductors exposed to moving magnetic fields.
By removing the laminated metal stator the largest cause of eddy losses is removed.

In addition some eddy current losses occur inside the stator coil. This is reduced by using thin magnet wire in parallel to get required cross section, so called litz wire. Alternatively, the windings may be made of thin metal foil that is insulated and rolled to a coil.

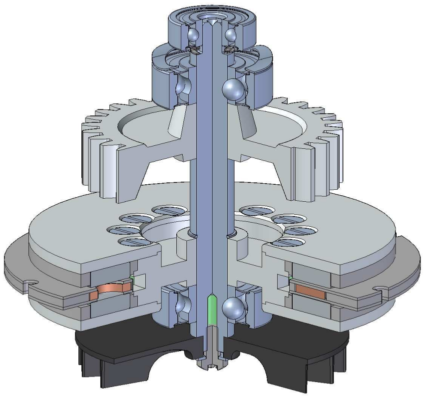

Figure 3: Coreless Motor and Fan

To keep the coils in place between the two permanent magnet rotors a holder of alumina is used. It is a strong non-conducting, non-magnetic ceramic. It is also a good heat conductor and is easily mass produced. Coils can readily be bonded to the alumina holder using suitable adhesives [9].

Using the suggested coreless motor for high RPM with low losses, the propulsion unit has the benefit of low loss coasting associated with a freewheeling mechanism, but also allows regenerative braking and reverse traction, useful for velomobiles.

3.7 Main Motor Considerations

The brushless motor used in hub motors is a so-called "outrunner", a motor with the stator inside of the rotor. This design has a large field diameter and this results in a higher torque compared to a similar sized motor with stator on the outside of the rotor.
In addition, the high power to weight ratio of the outrunner design is also beneficial for this application [10].

For the prototype the initial stator chosen was made for a radio controlled helicopter motor having outer diameter of 110 mm. This stator was also designed to be LRK wound [11].

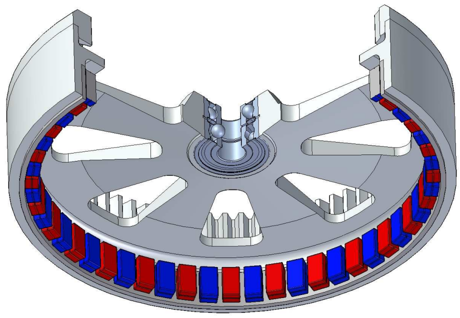

Figure 4: Outrunner Rotor

Due to cost and ease of manufacturing, the stator and rotor will be replaced with parts from standard bicycle hub motor with similar specification to the initial LRK design [12].

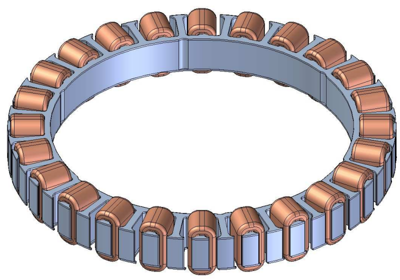

Figure 5: Outrunner Stator

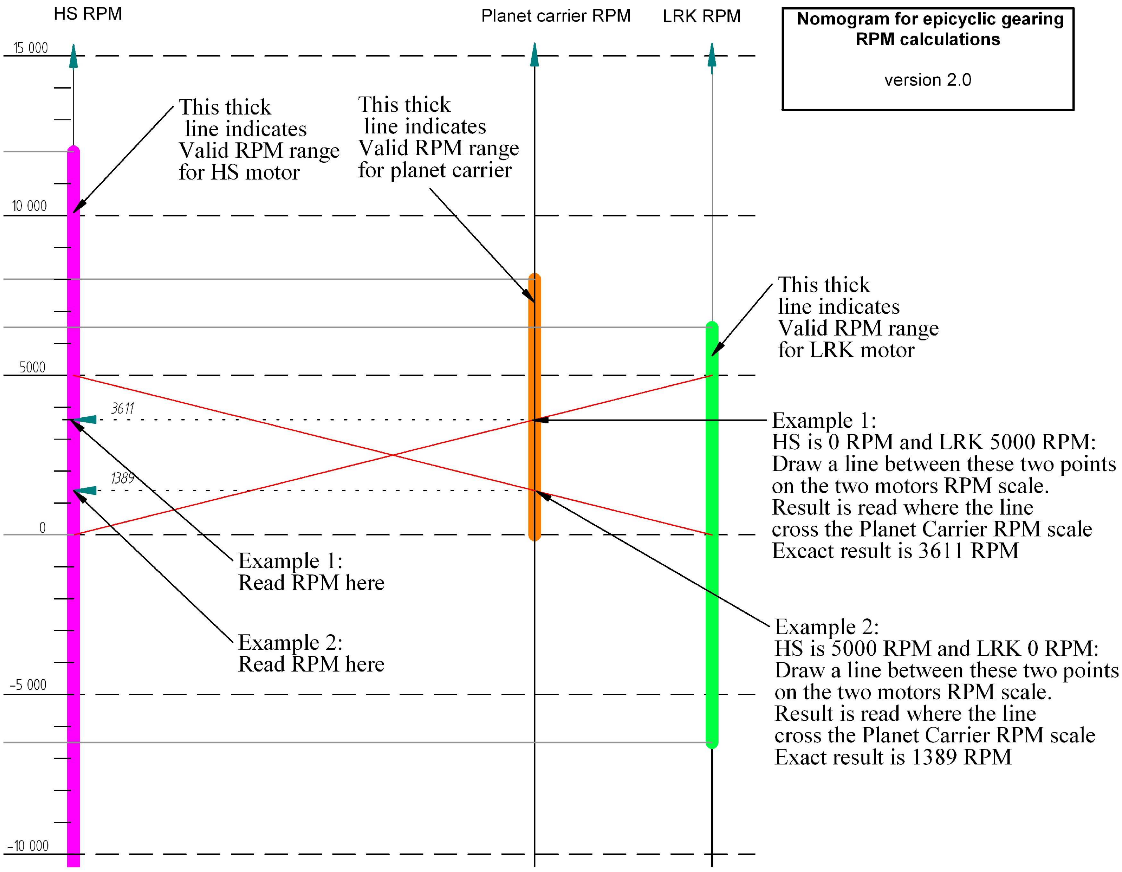

Figure 6: Nomogram for Epicyclic Gearing

4 Epicyclic Gearing

The epicyclic gear hast two input gears, sun gear and ring gear. The epicyclic ring gear is directly attached to the rotor of the main motor, while the sun gear is driven by the coreless gearing motor.

The ring of the original prototype design has 78 teeth and the sun 30 teeth while the planet gears have 23 teeth each. This epicyclic gear ratio is identical to the ratio used in the Toyota Prius *power split device* – PSD. The PSD is used for matching the engine speed to the road speed using an additional electric motor/generator and the same gear ratio was chosen since this was a well documented design and the Prius PSD was the inspiration for this new design [13].

On the Prius, the sun gear is driven by the gearing motor, and the planet carrier is driven by the internal combustion engine (ICE). The ring gear is the output.
On the new design, the gearing motor is still connected to the sun gear, but the planet carrier is the output and the ring gear is driven by the main motor. The reason for this change is to make it easier to shrink the gearing mechanism and to integrate it with the motors.

For the revised prototype the ring gear is taken from the same hub motor as the main motor parts to save time and cost. This will result in a higher epicyclic gear ratio and a slightly reduced ring gear diameter.

4.1 Nomogram of Epicyclic Gearing

To ease design of motors and gearing the use of a nomogram is very helpful when working with epicyclic gearing. It shows directly the relation between motor speeds and vehicle speed.
A nomogram for the 78/28 teeth ring/sun gear is shown in Figure 4. The thin red lines are used to find the speed of the last gear based on the speed of the two other gears.

Further reading about nomograms can be found in the refererence section [14].

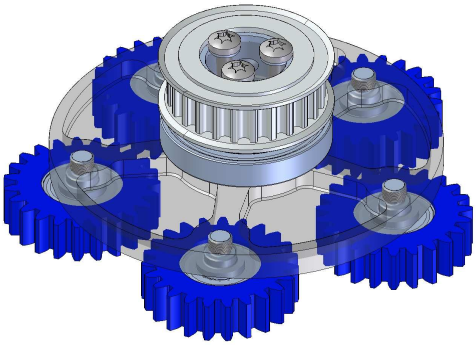

Figure 7: Planet Carrier

4.2 Planet Carrier

The planet gear carrier design has been stress analysed using finite element analysis software. This is a very important tool for achieving best possible strength and stiffness while keeping the weight low.

For noise and weight reduction the planet gears are made of a wear resistant polymer like POM or possibly glass-fibre filled nylon.

5 Power Transfer

Transmission of power from the propulsion unit to the wheel is done using a synchronous belt drive.
The pully on the planet carrier is fixed using a conical locking ring. By loosing three screws on the top of the planet carrier the pulley can be loosened and replaced to change final ratio.

Figure 8: Housing

6 Housing

The propulsion unit housing consists of two parts, base and lid.
The base contains fixing points and heat sink for forced cooling by air from the small fan. The end ball bearing also goes into the base.
The lid has a nitrile o-ring to make the housing water proof. It also contain the front ball bearing.

The housing is made of anodized aluminium with good mechanical strength, corrosion stability and good heat conductivity for cooling.

7 Control Electronics

Currently, the control electronics is yet to be designed. For the prototype standard brushless, sensorless motor controllers will be used for testing.

It is planned to use one Microchip DSP controller for each motor, plus a third identical DSP as master. These controllers are specially designed for brushless motor control [15].

7.1 Efficiency

The total system efficiency is mainly dependent on how well the main propulsion motor working load is kept.
This is accomplished by continous adjustments to the applied motor power and speed so the achievable systeml efficiency is highly dependent on regulation algorithm.
Here is a synopsis of the control algorithm:

- A) *set the most powerful motor (LRK) to a speed that is within range of epicyclic gearing for the wheel RPM and optimized for LRK efficiency*
- B) *set the speed of the smaller motor (HS) to a speed that matches LRK and wheel RPM (taken from a premade table in the master controllers program memory)*
- C) *check if wheel speed is correct (based on sensor input from pedal sensor, brakes, throttle, current sensors, temperature sensors)*
- D) *adjust target speed if needed based on input from C) and goto A)*

There exists some individual cases that needs special handling:

1. *Initiating sensorless LRK motor: The LRK is started running open-loop at a minimum speed. The HS will freewheel and the cycle will be stationary due to the HS motor not having much inertia. The HS will rotate backwards but will not brake since there is no current load.*
2. *Starting: The HS will be given a load by charging the battery as a generator. Increasing load will reduce the speed on the HS motor but the LRK speed is maintained by closed loop control so the output from the epicyclic will increase RPM and thus the speed of the cycle.*
3. *Coasting low-medium speed: The LRK will be more or less stationary and the HS will be free-wheeling up to 12000 RPM, having a coreless rotor it will not have iron loss and eddy losses should be very low due to stator being wound by very thin metal foil.*
4. *Coasting high-speed: The LRK is driven by voltage generated from HS to avoid over-revving the HS. Only enough energy to keep the LRK running is needed, thus low loss coasting should be possible at high speed.*
5. *Charging: The HS motor runs the cooling fan located on the motor axle. When charger or batteries get warm, the motor will need to start to prevent overheating. The LRK will run in oposite direction of the HS driven fan to keep the bicycle stationary. This has to be tightly controlled closed loop to prevent cycle from creeping slowly away.*

More information about the planned electronics can be found in the reference section[16].

8 Improvements

The new design has room for improvements in various fields.

8.1 Noise Reduction

The best possible noise reduction of the epicyclic gearing would be achieved by using helical gears. Unfortunately the cost of such gears, especially with internal teeth are quite high at low volumes.

Another means of achieving better noise reduction would be to run the gears in an oil bath. This is an option that is fairly easy to try out, others have tested this principle in standard hub motors. It is also described in the patent literature [17].

8.2 More Integration

The integration of the new design into a bicycle hub would be possible, but will increase complexity.
A better idea would be to integrate power and control electronics into the propulsion unit, making better use of the cooling fan and reduce wiring.

8.3 Cost Reduction

The current prototype design has been optimized for CNC machining from bar stock.. For mass production, a casting the housing, lid and planet carrier would probably be less costly.

The use of two separate motor controllers and a matser microcontroller is a quick and easy solution but not very cost efficient. Integrating control of both motors into fewer parts should be possible to do.

References

[1] Angel D. Ramirez Mosquera, “Plug-in Hybrid Electric Vehicles: A Viable Option for Sweden?”, Department of Energy and Environment, Division of Physical Resource Theory, Chalmers University, Göteborg, Sweden, 2007, table 3-3

[2] Wyczalek, F.A., *Ultra light electric vehicle parameters*, F.W. Lilly Inc., Bloomfield Hills, MI, USA, Jan 1996. ISSN: 0885-8985. in Aerospace and Electronic Systems Magazine, IEEE.

[3] Andreas Fuchs, *Analysis and Visualisation of Data Collected from Human-Electric Hybrid Bicycle-Tests*, Human Power eJournal Article 9 issue 2, October 15, 2005.

[4] Jonathan Weinert (UC Davis Institute of Transportation Studies), Chaktan Ma (Tsinghua University, Institute of Transportation Engineering), Christopher Cherry, (UC Berkeley Institute of Transportation Studies), *The transition to electric bikes in China: history and key reasons for rapid growth* published online 13 March 2007

[5] In EU the standard EN 15194:2009 and *Directive 2002/24/EC* limits continuous power to 250W.

[6] Toyota,

http://www.hybridsynergydrive.com/en/power_split_device.html accessed on 2009-04-15

[7] Horst Schulz et al., Fichtel & Sachs AG, Patent US3937309 *Multiple speed hub for a bicycle and like vehicle*

[8] Padmaraja Yedamale, Microchip, AN885 *Brushless DC (BLDC) Fundamentals*

[9] Alumina, Al2O3, has a typical heat conductivity of 25 W/mK and bending strength of 350 MPa

[10] Eckart Nipp, *Permanent Magnet Motor Drives with Switched Stator Windings* KTH, TRITA-EMD-9905 ISSN-1102-0172, page 78

[11] *Lucas, Retzbach and Kühfuss* (LRK) motors, also known as *Split Phase Sector* (SPS) motors. Mathcad models and related data can be found here: http://femm.foster-miller.net/Archives/examples/femm40/lrk40.htm accessed on 2009-04-15

[12] *Tongxin bicycle hub motors, http://www.tongxin.net.cn/en/index.htm* accessed on 2009-04-15

[13] E. A. hart, animation of the Toyota Prius Power Split Device (PSD) http://eahart.com/prius/psd/,accessed on 2009-04-15

[14] Molnar, John. *Nomographs.* Ann Arbor: Ann Arbor Science Publishers, Inc, 1981

[15] Daniel Torres, Microchip, AN1160 *Sensorless BLDC Control with Back-EMF Filtering Using a Majority Function*

[16] *Nohassel, http://groups.google.com/group/nohassel/web/electronics* , accessed on 2009-04-15

[17] Orville J. Birkestrand, Patent US6100615, *Modular motorized electric wheel hub assembly for bicycles and the like*

Authors

Per Hassel Sørensen,
Born Rogaland Norway 1962
Studied (1985-88) at Bergen Ingeniørhøgskole, now Bergen University. Works with product development of subsea and downhole instrumentation. Interested in electric vehicles for the last twenty years

Miles Hellon
Born Oxford U.K. 1955
Studied (1974-77) at London College of Furniture. Antique musical instrument restorer. Interest in electric bicycle design since 2003, particularly the integration of lightweight drives systems.